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Cosmic Dust Collection Facility: Scientific Objectives and Programmatic Relations

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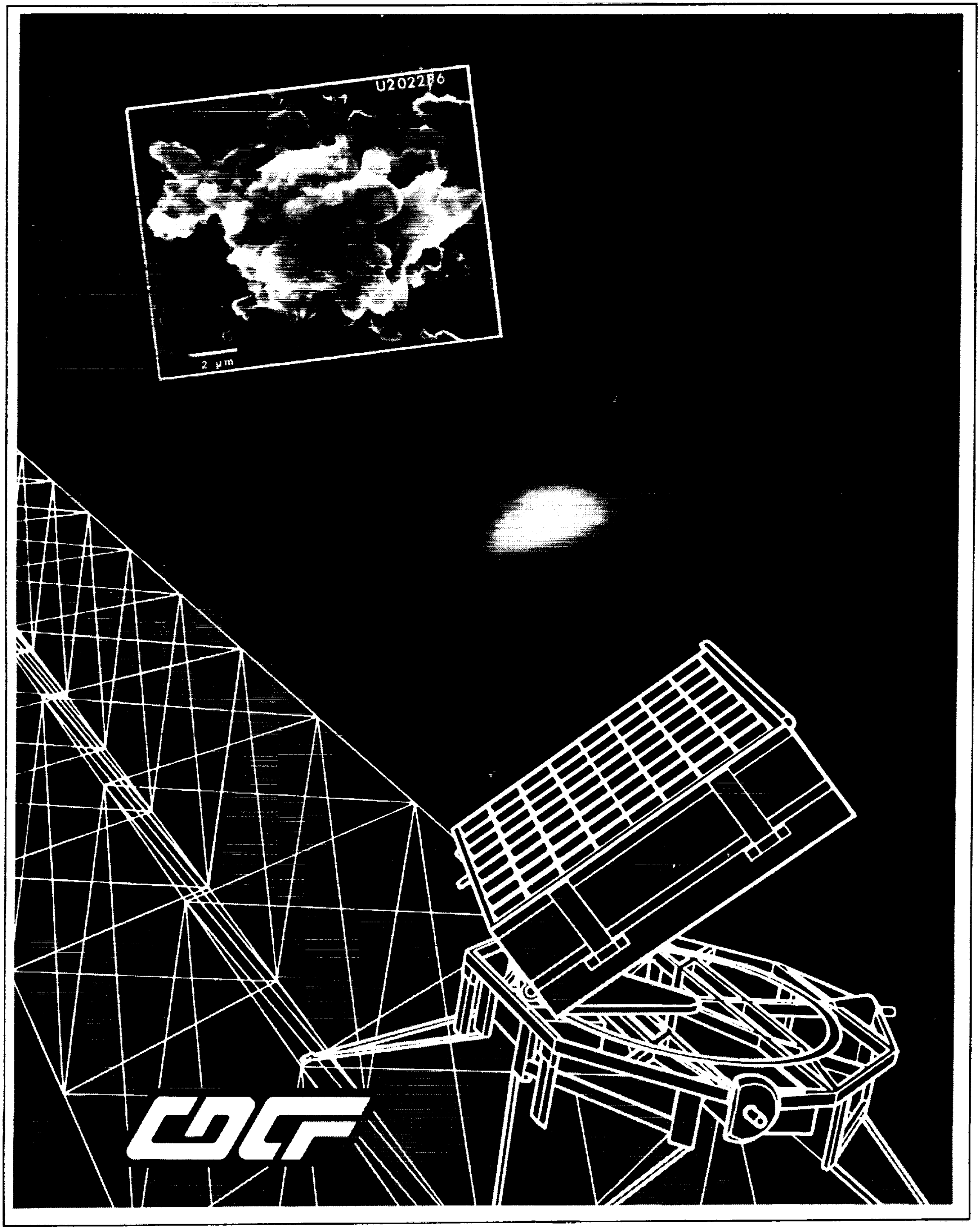

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FOREWORD

This report summarizes the science objectives for the Cosmic Dust Collection Facility (CDCF) on Space Station *Freedom* and relates these objectives to ongoing science programs and mission planning within NASA. The purpose of this report is to illustrate the potential of the CDCF project within the broad context of early solar-system sciences that emphasize the study of primitive objects in state-of-the-art analytical and experimental laboratories on Earth. Such a report might assist the science planners for the *Freedom* Station in the evaluation and comparison of attached payloads and their selection to flight-project status.

The report focuses on current knowledge about the sources of cosmic dust and their associated orbital dynamics, and it reviews the results of modern microanalytical investigations of extraterrestrial dust particles collected on Earth. Major areas of scientific inquiry and uncertainty are identified and it is shown how CDCF will contribute to their solution. General facility and instrument concepts that need to be pursued are introduced, and the major development tasks that are needed to attain the scientific objectives of the CDCF project are identified as well.

This report was written by the CDCF Steering Committee. It draws liberally from previous workshops dedicated to cosmic-dust investigations in low-Earth orbit and from the open scientific literature, yet referencing is kept to a minimum. This document is also responsive to the recommendations made by the Planetary Geosciences Strategy Committee, an advisory group to the Solar System Exploration Division (Code EL), in their final report on *Applications of the Space Station to Experimental Planetary Science* (January, 1988, 21 pp.).

I) EXECUTIVE SUMMARY

The purpose of this report is to review the scientific objectives and potential of the COSMIC DUST COLLECTION FACILITY (CDCF) as an attached payload on the *Freedom* Station. CDCF is designed to improve our understanding of interplanetary dust particles (IDPs), which harbor significant information about the early solar system:

> Some of these particles may be the most primitive solids in the solar system. They should give information on the physical and chemical processes that occurred during condensation of the solar nebula and the accretion of matter into planetary bodies.
>
> Information on the distribution and behavior of biogenic elements and the formative processes leading to simple compounds and complex molecules may be preserved in these dust grains.
>
> Identification and isotopic characterization of interstellar grains seems possible, either as specific components of IDPs that predate the solar system, or as contemporary grains that are intercepted by CDCF while they cross the inner solar system.
>
> Man-made particles in low-Earth orbit (LEO) can be characterized by CDCF, thus providing the opportunity for detailed study of the sources of orbital debris.

Provided by NASA and individual PI-teams, CDCF will consist of diverse instruments totaling approximately 10 m^2 in surface area, each able to

1) Measure the trajectories of individual particles with sufficient accuracy to permit identification of their parent bodies.

2) Decelerate these particles by the least destructive means and in a form suitable for return to Earth for subsequent mineralogical, chemical, isotopic, and organic laboratory analyses with state-of-the-art microanalytical methods.

Short of dedicated missions, detailed trajectory measurements are the only means of determining the astrophysical source(s) of extraterrestrial materials. While the study of interplanetary particles recovered from the stratosphere, polar ices, and deep-sea floors has already provided information not known from primitive meteorites, this information cannot be placed directly into a proper astrophysical context. Atmospheric entry has irrevocably destroyed their orbits: they are parentless objects. Additionally, any population of extraterrestrial particles collected on Earth is thought to be biased, because of the wide range of thermal histories -- including the total destruction of some particles by melting or vaporization -- that may be produced during atmospheric entry. A more representative particle population will be collected by CDCF, and new particle types may be found.

The trajectories of small interplanetary particles must be measured in space prior to atmospheric entry. Such measurements can be accomplished by employing existing sensor concepts, and when combined with orbital theory that accounts for gravitational and non-gravitational forces, it will be possible to assign individual particles to classes of parent bodies and possibly -- in fortunate circumstances such as meteor streams -- to specific primitive objects. This capability will be unique. An important gap that substantially influences current interpretations of the analytical results obtained from primitive extraterrestrial materials collected on Earth may therefore be closed by providing materials from known astrophysical sources.

The low flux of cosmic-dust particles demands inherently large surface areas for detection, as well as long periods of exposure, which will result in observatory-type, long-term (>10 years) operations for CDCF. This will also allow for the rotation of instruments and PI-teams, should superior instrumentation become available. The materials trapped in the collectors must be periodically returned to Earth for analysis. These features combine to render the *Freedom* Station as a highly suitable platform for CDCF. The largely autonomous mode of instrument operation is suitable for the early *Freedom* Station, as it necessitates only occasional harvesting of impacted collectors by robotic means and modest, periodic access to the Shuttle for return of these materials to Earth and for the transport of new collectors to the *Freedom* Station.

This report details current facility plans and major areas of instrument development necessary to accomplish the stated scientific objectives. It also contains a short summary of ongoing laboratory analyses of cosmic dust, which has largely been recovered from the stratosphere, to illustrate the power of current microanalytical methods in extracting textural, mineralogical, crystallographic, chemical, isotopic, spectral, and organic information from exceedingly small samples. Some resulting implications for solar-nebula processes, exobiology, and astrophysical observations are offered. The study of impact features on materials recovered from the Solar Maximum satellite provides proof that analyzable material may be recovered from LEO by collectors that are based on collisional deceleration of high-speed particles.

The report concludes with a programmatic overview that illustrates how the CDCF science objectives relate to major, ongoing programs of national and international interest:

> After exploring the inner solar system, most solar-system exploration strategies focus on the nature of primitive objects as exemplified by the vigorous study of primitive meteorites and the planning/ execution of dedicated missions to comets, such as GIOTTO, CRAF, and ROSETTA. IDPs are the most appropriate samples to provide "groundtruth" for these missions; measured IDP properties will affect the selection and design of suitable mission instruments, and will benefit the analysis and interpretation of actual flight data.
>
> Advancements in our understanding of the origin of life also mandate detailed characterization of the most primitive solar-system objects. Observations of natural materials will reveal the initial distribution and behavior of biogenic elements, and will identify important precursor compounds of life and their formative processes.
>
> Characterization of the smallest and most primitive natural solids in our own solar system will form a natural link to astronomical observations of similar-size particles outside the solar system. The potential to recover such interstellar grains and to analyze their isotopic compositions is of fundamental importance to astrophysics and the understanding of nucleosynthesis.
>
> The potential of CDCF for enhancing our understanding of early solar-system processes is emphasized throughout this report. In addition, CDCF will yield insight into contemporary processes concerning the dynamics of small particles and their fluxes, which are scientifically rewarding in their own right. Combining the study of dynamical properties of natural particles with improved characterization of man-made debris in low-Earth orbit will allow substantially better definition of the collisional hazards to spacecraft, a subject of urgent engineering concern to all space-faring parties.

II) HISTORICAL BACKGROUND

The smallest solids that exist in the inner solar system are commonly referred to as "micrometeoroids", "interplanetary dust particles" (IDPs), or "cosmic dust". They are of long-standing astronomical interest as they are macroscopically manifested in the zodiacal cloud. A variety of forces, gravitational and non-gravitational, lead to continual losses of particles from this cloud; in order to maintain long-term cloud stability, it is necessary that sources for continued replenishment of dust-size particles exist. Comets and asteroids are believed to be the most prolific sources, although their relative contributions are difficult to quantify (Whipple, 1967; Dohnanyi, 1978; McDonnell, 1978; Giese *et al.*, 1985; Leinert and Grün 1989).

Modern space exploration provides the opportunity to perform *in situ* measurements by space-borne instruments, thus complementing and expanding on telescopic observations. An intense period of such investigations was spawned in the sixties. Initial *in situ* measurements were largely motivated to define the collisional hazard and its mitigation for Apollo hardware, yet substantial scientific issues were addressed and discovered as well by the early EXPLORER, MARINER, PEGASUS, and other missions. The PIONEERS 8 through 11, LEAM, HELIOS, and HEOS, launched in the sixties and seventies, yielded substantial insight into the radial and latitudinal distribution of dust (*e.g.*, McDonnell, 1978).

Sensors flown on these missions were designed to yield dynamical properties of dust particles, such as relative speed, kinetic energy, momentum, or mass, as well as precise timing for the actual collisional events. These sensors provide substantial flight heritage for the instrument concepts considered for CDCF. Successful design and deployment of cosmic-dust flight instruments continued into the eighties culminating recently in the spectacular GIOTTO and VEGA missions to comet Halley. These latter spacecraft had several dust instruments on board, including mass spectrometers for the measurement of the elemental and isotopic compositions of individual particles (*e.g.*, Kissel *et al.*, 1986a, 1986b).

The return of lunar samples also provided novel opportunities to study cosmic dust. Lunar rock surfaces display abundant microcraters generally less than a millimeter in diameter; the frequency of such craters reflects our most reliable knowledge of the relative mass frequency of natural hypervelocity particles for masses from 10^{-19} to 10^{-6} g (Morrison and Clanton, 1979). As revealed by its comminuted surface and fine-grained regolith components, the Moon also demonstrated that interplanetary dust has been present in the inner solar system for at least 3.8 billion years.

After many previous efforts to find cosmic-dust grains on Earth had failed, a most significant breakthrough in cosmic-dust studies occurred when Brownlee (*e.g.*, Brownlee, 1978) demonstrated for the first time that extraterrestrial particles may be recovered in the stratosphere by high-altitude aircraft. Purposeful application of modern microanalytical methods provided the cornerstone for Brownlee's success; diagnostic mineralogic and chemical information could be extracted from samples some 10 to 20 micrometers in size, allowing distinction of extraterrestrial materials from terrestrial contaminants. Many additional analyses, including measurements not possible in the late seventies, have by now established beyond doubt the extraterrestrial nature of these particles. Indeed, a wide variety of extraterrestrial particle types are now recognized that differ substantially in physical, mineralogic, chemical, and isotopic properties (*e.g.*, Brownlee, 1985; Bradley *et al.*, 1988; or Mackinnon and Rietmeijer, 1987). These findings are briefly reviewed in Chapter V, as they constitute the primary motivation to capture particles in space for return to Earth. The analytical criteria developed to identify extraterrestrial particles in the stratosphere led to rejuvenated, and by now successful searches for cosmic dust in deep-sea sediments (*e.g.*, Brownlee, 1981) and pre-industrial polar ices (*e.g.*, Maurette *et al.*, 1986; Zolensky *et al.*, 1987). Collection of stratospheric particles *via* high-altitude aircraft became a formal part of NASA's Extraterrestrial Materials Program, and laboratory analysis of cosmic dust is now an effort of international scope. The analysis of cosmic-dust particles evolved into an integral and substantial part of extraterrestrial material studies concerned with the early solar system (*e.g.*, Kerridge and Matthews, 1988).

Although a wide variety of significant laboratory measurements are possible on particles collected on Earth, indirect arguments and inference are the only means to place them into a proper astrophysical context. We have no direct knowledge from where these particles originated, nor do we know if comets or asteroids are the dominant sources. All trajectory information is lost for particles collected on Earth, as it is irrevocably destroyed during atmospheric entry. Identification of any parent object(s) mandates that (a) the trajectories be measured on a particle-by-particle basis prior to atmospheric entry, and (b) a thorough theoretical understanding be in place as to how the particle's orbit may have evolved after separation from its parent body. The orbits of a (massive) parent/(small) daughter pair diverge immediately upon release of the daughter due to the ejection velocity of the daughter; gravitational forces continue and new, non-gravitational forces will enter, as described in Chapter IV, that substantially affect the long-term orbital evolution of the small daughter particles.

The basic capability to measure the trajectories of individual hypervelocity particles from a platform in LEO exists; a variety of sensor concepts employed previously may be adapted. Surfaces returned from space, such as from the repaired Solar Maximum satellite, provide proof that analyzable particle residues can be returned from LEO, even more so if improved capture technologies are considered (see Chapter VI). These developments combine into the motivation to expose cosmic-dust instrumentation on Space Station.

A facility-class, attached payload is envisioned, formally known as the COSMIC DUST COLLECTION FACILITY (CDCF). The purpose of all instruments on this facility is to measure the trajectories of individual particles, to assign them to astrophysical sources, and to return analyzable, primitive materials to Earth for subsequent laboratory study. This capability would be unique and constitutes the scientific justification for CDCF.

The *Freedom* Station provides a suitable platform, as detailed in the following chapter that gives an account of current plans for the facility. Subsequent chapters detail our present understanding of particle sources (Chapter IV) and summarize the results of laboratory analyses (Chapter V). Current instrument capabilities and major development tasks to accomplish the stated objectives are the subject of Chapter VI. The report concludes with a programmatic overview that relates the expected contributions of CDCF to ongoing national and international programs (Chapter VII).

III) CURRENT FACILITY PLANS

IIIa) PROGRAMMATIC OVERVIEW

Current plans for the Cosmic Dust Collection Facility are the result of a number of workshops dedicated to cosmic-dust studies in LEO (Walker, 1983; Hörz, 1986; Mackinnon and Carey, 1988) and the recommendations by the Planetary Geosciences Strategy Committee (NASA, 1988). They also accommodate various conceptual studies performed by individual experts and by a formal Project Study Team at the Johnson Space Center. These preliminary studies were sponsored by the Solar System Exploration Division (Code EL) and by the Life Sciences Division (Code EB) within NASA's Office of Space Sciences and Applications (OSSA). A Memorandum of Agreement between both divisions identifies the Solar System Exploration Division as having primary project responsibility. A program plan issued by Code EL provides programmatic guidance and identifies JSC as NASA's Lead Field Installation for the development and implementation of this project.

CDCF is a facility-class, attached payload that will expose about 10 m^2 of instrumented surfaces to the natural and man-made particle environment on the *Freedom* Station. Separate instruments will be provided by NASA (approximately 60% of surface area) and by independent principal investigators (approximately 40%). The purpose of the general-user instruments built by NASA is to provide a largely analytically oriented community (that is not interested or expert in providing flight hardware) with the opportunity to analyze primitive materials. The cosmic-dust samples returned from CDCF will be a new class of extraterrestrial material, and the agency-collected specimens will assure broad-based participation in their analysis as part of NASA's ongoing Extraterrestrial Materials Program. The principal-investigator instruments will be designed, built, and analyzed by the responsible individual(s) selected for flight participation. This report is sufficiently general to identify concerns regarding the development of both the general-user and PI instrument(s). Ideally, specific designs will be sufficiently different to permit the selection of complementary approaches and objectives for the integrated facility.

The facility will be designed for long-term, observatory-style operations, owing to the small flux of cosmic-dust particles and the desire to collect statistically significant and representative particle populations; in addition, temporal variations of the dust environment are of scientific interest. The initial design will include provisions for physical expansion of the facility during the mature *Freedom* era; it will also permit for exchange and rotation of instruments by investigators other than those selected initially, and will allow testing and incorporation of innovative designs. Dedicated ground operations will be required for long-term facility support, which entails the daily monitoring of the facility, the periodic harvesting of particles, their processing, allocation and curation, and their vigorous analysis. Suitable state-of-the-art analytical methods to characterize exceedingly small samples will constitute an integral and important part of the overall system capabilities.

IIIb) DEFINITION OF SCIENCE REQUIREMENTS

Current knowledge of the cosmic-dust environment, such as the relative mass frequency of particles, their absolute flux and velocity distribution, and the physical, chemical and isotopic properties of individual particles drive the design of the facility and its instruments. First-order scientific considerations related to the mechanical architecture of CDCF will be introduced below; additional factors that affect the design of specific instruments will be detailed in Chapter VI.

Current best estimates for the cumulative flux of interplanetary dust in LEO as a function of particle mass are illustrated in Figure 1a. There is general concensus that these estimates are accurate within a factor of five; however, more definitive flux versus mass measurements are among the primary CDCF objectives. The velocity distribution is shown in Figure 1b and refers to various observations of meteoroids 10^{-5} to 10 g in mass that enter the atmosphere; the velocities given are suitably corrected to reflect pre-atmospheric velocities in LEO. Vectorial addition of particle and spacecraft velocity (7.6 km/s) will determine the relative collision speed in a moving spacecraft reference frame (Zook, 1987). A wide aperture facility/instrument configuration seems obvious, ideally observing the entire sky, so as to access all possible particle sources. However, practical considerations impose severe limits on absolute aperture width and thus the physical reorientation of instruments becomes desirable.

It is obvious from Figure 1a that the low particle flux demands inherently large surface areas to collect a statistically significant sample population. The objective is to collect a few hundred particles $>10^{-9}$ g in mass (>10 μm in diameter). This requirement is based on the wide diversity of particle types currently recognized (see Chapter V). The classification of a particle population into meaningful compositional groups and associated astrophysical sources is possible only if large numbers of representative particles are studied. The above mass or size limit is somewhat arbitrary, yet it allows -- within current analytical methods -- a wide variety of measurements; substantially smaller particles may be investigated only by a limited subset of methods. In addition, textural context and detailed phase-assembly information (*i.e.*, coexisting phases/processes?) may be lost in exceedingly small samples. In more practical terms, the analysis of ever decreasing masses will become increasingly more cumbersome, and specific measurements will approach sensitivity thresholds of analytical instruments, affecting measurement accuracies. Inevitably, a point of diminishing returns will be reached that will, however, vary from method to method. The collection of particles <10 μm is, nevertheless, a desirable goal.

Because spacecraft velocity affects relative collision speed, any instrument that points in the direction of spacecraft motion (apex direction) will intercept particles at substantially higher mean velocities than an instrument pointing in the opposite (anti-apex) direction. As a corollary, the absolute particle flux is sensitively related to the pointing direction as well, with the apex-pointing surface intercepting approximately six times the number of particles that an anti-apex pointing instrument would encounter. This leads to scientific trade-offs between the absolute collision velocity, acceptable particle degradation during capture, and the absolute number of particles collected. One extreme endmember is the anti-apex facing instrument which is optimal for the capture objective (some 30% of all particles encountered are expected to have speeds <10 km/s), but which is the worst case in terms of particle flux (approximately ten particles >10 μm/yr/m^2). These (recurring) trade-offs are best accommodated by requiring the capability to reorient the instruments periodically. The ability to observe any specific radiant should be included; in this way, favorable instrument pointing during specific meteor streams would be possible.

IIIc) CONCEPTUAL FACILITY DESIGN

Figure 2 illustrates a conceptual facility architecture that accommodates the major science requirements: a planar array (~3.3 x 3.3 m in surface area and ~1 m deep) that can be reoriented azimuthally about a vertical axis (360°). Furthermore, the entire array is hinged to allow variable inclination about a horizontal axis (between 0° and 90°). These features provide for reorientation capability of all instrument surfaces and accommodate the basic requirements to: (1) access the entire sky, (2) select some very specific radiant on occasion, and (3) allow periodically for different trade-offs between relative collision velocity and particle yield(s) that may be "tailored" within the limits described above.

Figure 2 shows a view of the facility's front side and schematically depicts the modular concept proposed for all instruments and their principal components: the trajectory sensor and the capture device. Modular instrument buildup *via* standardized interfaces seems advantageous for the accommodation of diverse instruments. Removal of fractional surfaces (*i.e.*, of easily interchangeable "modules") will also be needed during harvesting operations and concurrent replenishment with pristine modules. Furthermore, modular design would be favorable for substitution by innovative instruments and for repair or replacement of failed components. In addition, all sensors must be integrated with a single, central data system. A modular design will also minimize the routine demands on the resources (*i.e.*, mass,

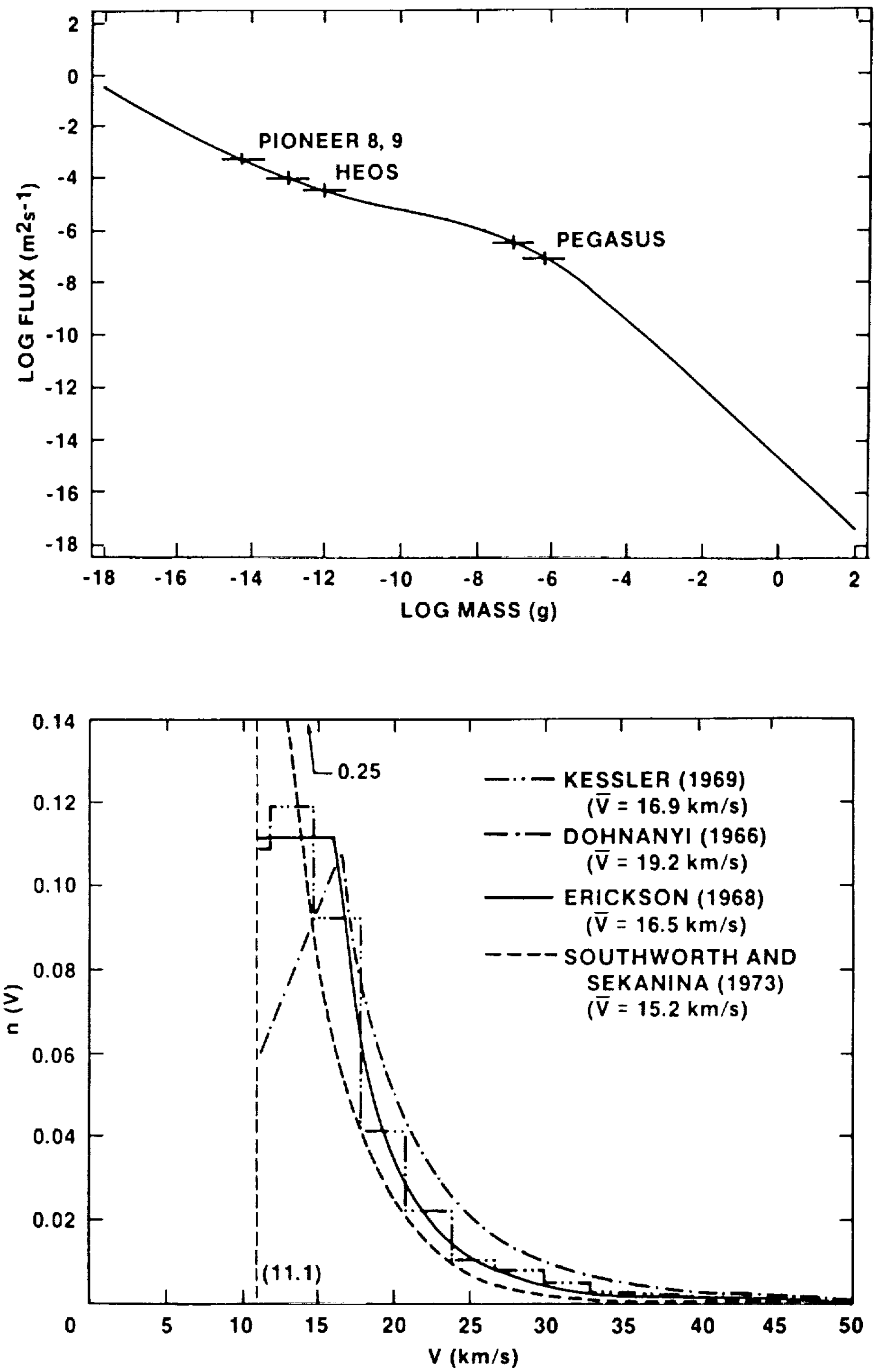

FIGURE 1. (a) The cumulative mass-frequency distribution and associated flux of micrometeorites (adopted from Grün *et al.,* 1985). (b) The velocity distribution of photographic and radar observations of meteoroids normalized to Earth (from Zook, 1975). Note that the space-station velocity vector (approximately 7.6 km/s) may be either subtracted or added vectorially to these velocities, depending on specific instrument orientation.

COSMIC DUST COLLECTION FACILITY

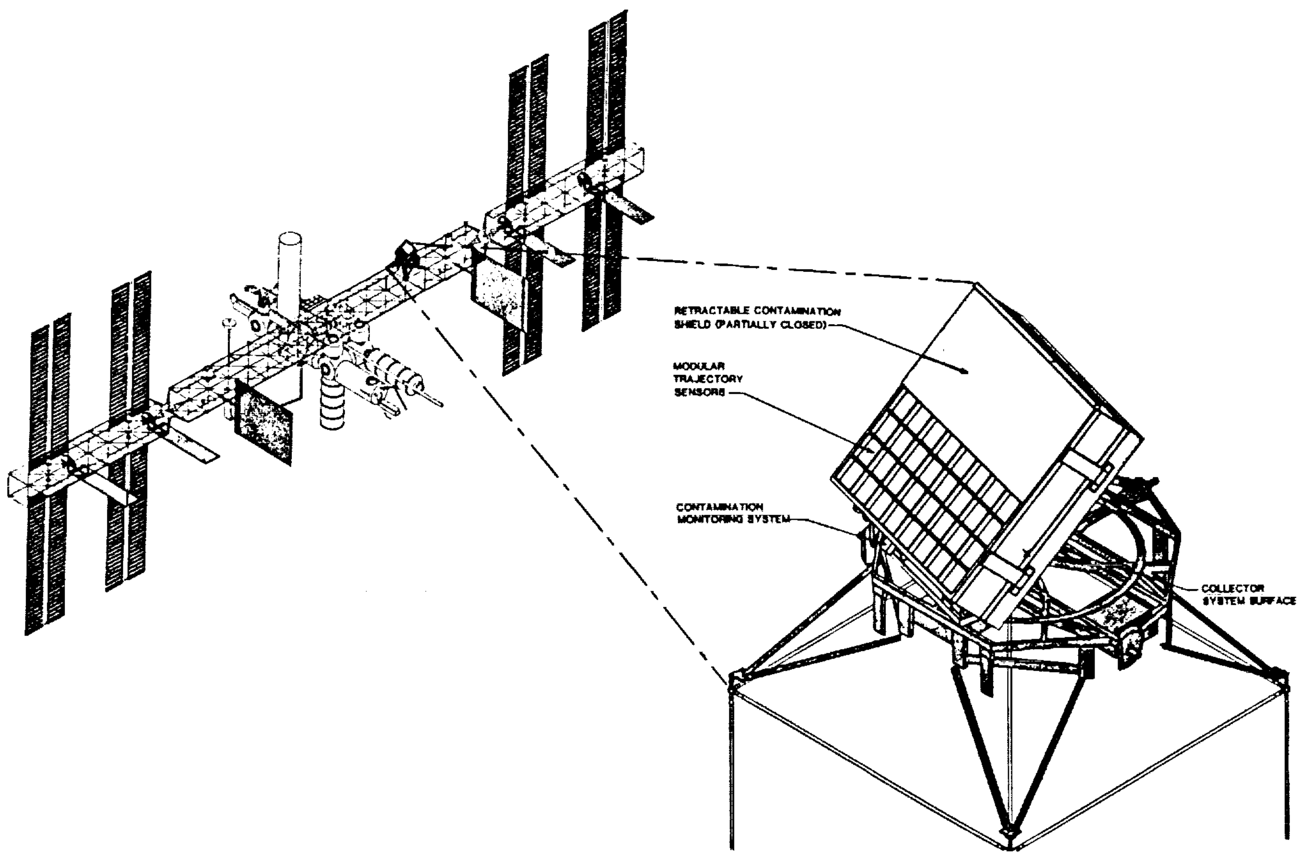

FIGURE 2. Preliminary structural design of CDCF accounting for the first-order science requirements, such as repositioning into any orientation *via* a vertical and a horizontal axis, accommodation of modular instruments, and a total instrument surface of some 10 m^2 (and approximately 1 m in depth). Also included are features to monitor/protect against intolerable contamination, and it is envisioned that appropriate repositioning of the array into some harvesting mode will allow the telerobotic system to access both the front (*i.e.*, trajectory sensors) and the rear surface (*i.e.*, collector modules).

volume, etc.) of the Space Transportation System to shuttle harvested modules and their pristine replacements to and from *Freedom*; periodic harvesting/retrieval of fractional surfaces will be accomplished readily with a modular design because only that subset of collectors which suffered impact will need to be harvested and transported. All instrument modules will be designed to permit robotic harvesting and concurrent replacement with pristine collectors; such harvesting/ replacement operations will occur every 90 days, as available.

A central data system (not illustrated) will be part of the facility and will provide power, signal acquisition/processing capabilities, and telemetry links for all instruments; this system will also acquire all navigational information from the *Freedom* Station that is needed to obtain geocentric particle trajectories. Auxiliary CDCF features include an active contamination monitoring system and a mechanical contamination barrier that may be closed during periods when intolerable amounts of contaminants are known or suspected to be present.

The Johnson Space Center (JSC), Houston, was selected as the agency's Project Lead Field Installation responsible for the development and implementation of the CDCF Project. JSC will provide the structural facility design, the central data system, and the general-user instruments. These activities entail the definition and accommodation of all interfaces (*i.e.*, mechanical, electrical, and operational) with STS and the (evolving) Space Station. An efficient ground operation will be emplaced for long-term operations, including all ground-to-facility telemetry, electronic networking to flight-instrument PI's, rapid distribution of PI-supplied capture devices, processing of the user instruments, and allocation/ curation of the general-user specimens.

IV) THE SOURCES OF COSMIC DUST

At present, the relative contributions of comets versus asteroids to the inventory of interplanetary dust are not well determined. Some direct observations on particles released from comets exist, but not from asteroids. Nevertheless, a wide variety of calculations identify comets and asteroids as the major sources of interplanetary dust. Interstellar particles and impact ejecta from other planetary objects or their moons appear to be minor contributors at best. Unquestionably, the rare interstellar particle, if captured, would represent a scientific opportunity of historic significance.

There are no generally accepted diagnostic criteria to distinguish between comet- and asteroid-derived particles on the basis of laboratory observations alone. Sanford (1986) suggested that they may be differentiated by their solar-flare track densities because, on average, they should have different orbits and exposure histories; however, this idea remains untested. On the other hand, it is well established that a wide variety of particle types exist (see Chapter V) that may not readily be reconciled with a single primitive parent. Orbital theory, when coupled with analytical laboratory results, leads to the conclusion that the contemporary particle population is derived from a number of primitive parent bodies.

IVa) DUST SOURCES WITHIN THE SOLAR SYSTEM

The meteoritic complex in the inner solar system mandates some continued replenishment to maintain temporal equilibrium because particles are continually being destroyed by mutual collisions or lost by gravitational and nongravitational forces, including Poynting-Robertson drag and solar-wind drag. Whipple (1967) estimated the loss rate from the entire complex at about ten tons every second, and suggested that comets alone may be an adequate source to balance this mass loss. While most subsequent work corroborates this magnitude of mass loss (*e.g.*, Dohnanyi, 1972, 1978; Grün *et al.*, 1985; Giese *et al.*, 1986), some maintain that comets do not presently supply dust at rates even approaching ten tons per second. It has been suggested that additional mass might be supplied by asteroids (Dohnanyi, 1972, 1978; Sykes and Greenberg, 1986; Leinert and Grün, 1989). Some observational evidence by IRAS, faint "dust belts" in the asteroid region, may lend support to substantial asteroid contributions (Neugebauer *et al.*, 1984; Dermott *et al.*, 1984; Sykes and Greenberg, 1986) that may be as much as 50% (Zook and McKay, 1986). Growing and improved insight has also emerged from a number of experimental impact studies, which were designed to aid our understanding of the process of collisional fragmentation and the production of small dust grains from initially larger objects (*e.g.*, Dohnanyi, 1978; Sykes and Greenberg, 1986;

Leinert and Grün, 1989). Undoubtedly, collisional destruction of centimeter- to meter-sized objects has significantly contributed to the generation of small dust grains.

If comets were insufficient, and if asteroids were not substantial contributors, it would then be possible that the number of particles in the meteoritic complex may now be decreasing with time. The existence of a meteoritic complex essentially throughout solar-system history is well documented from lunar-sample studies. Therefore, the problem becomes one of understanding the long- and short-term stability of the dust cloud; what are the rate terms for various dust sources, and is the cloud presently in dynamic equilibrium? Such questions are difficult to constrain without additional observations (*e.g.*, Elsasser and Fechtig, 1976; McDonnell, 1978; Giese and Lamy, 1985). Undoubtedly, these uncertainties affect major planning activities for CDFC; however, CDCF may contribute to the solution of such questions in major ways.

One reason that the specific contributions of comets and asteroids are poorly understood at present is the lack of direct trajectory measurements. Direct orbit measurements in space *via* remote Earth-based methods are impractical for such minute particles and *in situ* instruments are needed; all told, only about 20 trajectories are available to date, measured by the Pioneer 8 and 9 instruments (Berg and Gerloff, 1971).

The scarcity of direct trajectory observations is presently compounded by an incomplete knowledge of the orbital divergence between a massive parent and its small daughter particle. The effects of gravitational and non-gravitational forces differ on a massive parent body and its smaller daughter particle. These forces lead to orbital divergence that strongly depends on the daughter's mass, density, albedo, the time elapsed since release, and the specific location and direction of release relative to the gravitational configuration of the sun and its planets. The physics underlying such calculations are well understood, yet the computations are massive and time consuming, even with the aid of modern computers. Without doubt, the virtual lack of trajectory measurements in past flight experiments provided little incentive to establish such a calculational base.

These prerequisite orbital-divergence calculations were initiated recently as part of the conceptual study phase of CDCF. They include the effects of radiation pressure, Poynting-Robertson drag, and solar-wind drag, as well as gravitational perturbations by the planets and the parametric modeling of different physical properties such as the mass, density, and reflectivity of the particles (Gustafson *et al.*, 1987; Jackson, 1987; Jackson and Zook, 1989). Obviously, very small masses diverge more rapidly than more massive daughters and any parent/daughter association becomes less apparent with increasing elapsed time since separation. Many particle orbits may have evolved into complex parent/daughter relationships that may not be readily reconstructed from a measured particle trajectory. On the other hand, specific sources in the form of single-parent objects can still be recognized with relative ease from encounters with specific meteor showers, where little divergence from the parent comet has occurred. Furthermore, preliminary results indicate that a broad distinction between cometary and asteroidal sources seems possible, even for highly evolved dust orbits.

The main purpose of the ongoing calculations is to develop criteria for the recognition of parent/daughter relationships that can be applied to progressively more extreme cases of orbital divergence. Such calculations will form the qualitative and quantitative basis for the evaluation and proper interpretation of the first direct measurements of many particle trajectories as provided by CDCF. As an important by-product, such calculations will also define the precision with which the trajectories will actually have to be measured in LEO to make successful source assignments.

Other sources of natural, small particles within the solar system are possible. These include the Sun and fine-grained ejecta from planets and their moons and rings (Alexander *et al.*, 1987; Sanford, 1987), yet all seem to be minor contributors in view of the mass fluence needed to maintain the zodiacal cloud.

IVb) INTERSTELLAR SOURCES

Interstellar dust grains should enter the solar system as the Sun sweeps through the interstellar medium. While a variety of particles may readily enter and cross the outer solar system, it is not clear what types of particles, especially at masses $<10^{-10}$g, may reach the inner solar system (Gustafson and Misconi, 1979). Modeling of relevant processes is limited because of many assumptions that must go into the definition of associated boundary conditions. A particularly troublesome area is the interaction of these charged particles with the Sun's dynamic electromagnetic field, which is only characterized within the ecliptic plane; such interactions may prevent small, micron-sized particles from reaching the inner solar system. Unquestionably, interstellar particles will have high velocities and should be traveling on hyperbolic orbits that clearly distinguish them from dust sources within the solar system. Thus, while it is difficult to calculate the flux of interstellar particles, most can be readily identified by trajectory measurements.

The identification, recovery, and laboratory analysis of interstellar solids seems possible *via* CDCF, provided interstellar particles reach the inner solar system in the first place. The instrumentation proposed for CDCF represents the most promising approach to address this question, and may provide the historic opportunity to obtain direct laboratory measurements on individual grains that have demonstrable interstellar origins.

IVc) MAN-MADE PARTICLE SOURCES

A substantial source of small particles, confined and unique to Earth orbit, will be encountered by CDCF in the form of man-made orbital debris (Kessler and Su, 1985). Such material comes in large chunks (spent spacecraft) and myriads of small particles from collisionally fragmented satellites, accidental explosions, and the firing of solid-fuel rocket motors. CDCF can make substantial contributions to improved characterization of this man-made orbital-debris environment. The CDCF instruments include all requirements needed to characterize small orbital debris; indeed, it is inevitable that CDCF will obtain orbital-debris information as the investigation of natural particles demands the recognition of other particle types and their sources. By definition and design, CDCF is well suited to monitor the dynamic evolution of the orbital-debris environment during the next decade, and especially that of individual, prolific sources. Thus, CDCF may be viewed as an agency resource contributing to the definition and mitigation of collisional hazards in low-Earth orbit as well.

In conclusion, the potential contributions of CDCF to the solution of these dynamic problems may be summarized as follows:

1) Definitive measurements of the flux and mass distribution of all particles that exist in LEO will be made.

2) Statistically significant numbers of trajectories will be measured to determine the relative contributions of comets and asteroids.

3) Particles released relatively recently may be assigned to specific parent objects.

4) The opportunity exists to identify, trap, and analyze interstellar particles should they traverse the inner solar system.

5) Substantial refinement in the understanding of the dynamic properties of orbital debris and their sources will be accomplished.

V) LABORATORY ANALYSIS OF COSMIC DUST

This chapter briefly summarizes current analytical results for interplanetary particles that have been collected on Earth. The purpose is to illuminate the contributions already made towards a more detailed characterization of early solar-system processes and to demonstrate the need for continued, vigorous cosmic-dust research. Recall that no particle analyzed to date can be associated unambiguously to any astrophysical source, and that selective particle destruction during atmospheric entry may have produced a biased sample population. While the capture techniques considered for CDCF may introduce some bias of their own, it will nevertheless be possible to greatly augment our understanding of the diversity of natural particles *via* CDCF samples. The prospect of analyzing particles from known primitive objects constitutes a unique opportunity for cosmic-dust studies that may be surpassed only by dedicated missions to primitive objects.

Va) MAJOR COMPONENTS AND RESULTING CLASSES OF PARTICLES

Among the most significant results of the laboratory investigation of extraterrestrial particles is the recognition of a wide diversity of particles possessing diagnostically different mineralogic, chemical, and isotopic compositions. The diversity of phase assemblages and the coexistence of specific phases is indicative of a number of formative processes. This particle diversity does not seem to result from a simple process occurring in thermodynamic equilibrium; a variety of processes are required, including the reprocessing of preexisting materials by, among others, aqueous alteration, melting, and partial evaporation.

Particle textures range from compact, smooth grains to complex and highly porous, low-density aggregates. The intrinsic grain size of component minerals is highly variable in the compact particles and includes specimens composed entirely of large, single crystals. The porous and fluffy aggregates have grain sizes generally <1 μm, although, particles smaller than 0.01 μm are known. The detailed mineralogical and chemical characterization of such exceedingly small samples, typically some 10 to 20 μm in diameter (Zolensky and Mackinnon, 1985), attests to the powerful capabilities of modern microanalytical methods.

On the basis of major-element composition that is intimately related to the dominant mineral phases, two particle classes are distinguished: "chondritic" and "non-chondritic". Each class may be subdivided into subclasses, with each subclass being distinct and significant in terms of specific formative processes (*e.g.*, Zolensky, 1987; Mackinnon and Rietmeijer, 1987; Bradley *et al.*, 1988). Brownlee's initial discovery of "extraterrestrial" dust referred to chondritic particles because they were obviously the most likely materials for which a (compositional) relationship to primitive solar-system materials could be demonstrated, specifically to carbonaceous chondrites. The recognition of non-chondritic samples as extraterrestrial materials is difficult on occasion, resting in part on independent isotopic evidence, and in part on analogous, although not exactly identical, materials in meteorites.

The CHONDRITIC PARTICLES recovered from the stratosphere have received the greatest attention to date. Two distinct subclasses exist: ANHYDROUS and HYDROUS. Each group, however, displays mineralogic variability with the anhydrous materials being further subdivided into olivine- or pyroxene-rich types. The hydrous particles differ in their dominant hydrated layer-lattice silicate, resulting in the smectite- and serpentine-bearing subclasses. The smectite-rich subclass is the most abundant accounting for approximately 50% of all chondritic particles.

ANHYDROUS CHONDRITIC PARTICLES are commonly highly porous aggregates. They contain olivines of variable Fe content (Fo_{40-100}), diverse pyroxenes (enstatite, hypersthene, fassaite, diopside, augite), magnetite, kamacite, various Fe- and Fe-Ni sulfides, carbides, chromite, some silicate glass, and carbonaceous material (for a review see Mackinnon and Rietmeijer, 1987). Individual minerals exhibit significant morphologic diversity, ranging from anhedral to euhedral, including platelets, rods, and whiskers, the latter possibly formed by condensation. Relative frequency of these minerals (*i.e.*, modal composition) is highly variable and not all phases are present in every particle. Variable phase assemblages and textures attest to a wide range of temperatures and other conditions during the formation of individual phases.

HYDROUS CHONDRITIC PARTICLES are generally more compact, less porous than anhydrous particles, and contain layer-lattice silicates in addition to olivine, pyroxenes, carbonates, glass, and carbonaceous materials. The presence of hydrated layer-lattice silicates, dominated by Fe-Mg smectites and serpentine, seems to require aqueous alteration (Zolensky and McSween, 1988).

One of the major and most intriguing constituents of most chondritic particles is diverse CARBONACEOUS MATERIAL. Unfortunately, it remains poorly characterized because of current analytical limitations. Raman spectra and associated luminescence observations were recently accomplished on single, chondritic dust grains (Wopenka, 1988). To date, most spectra identify the presence of highly disordered, if not amorphous carbons, a conclusion that also accounts for the observed luminescence characteristics, and that had been previously inferred from TEM observations. On the basis of comparisons with synthetic materials, some particles may contain microcrystalline domains of aromatic compounds <25 Å in size. The Raman spectra of these particles show certain similarities with telescopic observations of galactic objects, the emissions of which are thought to be dominated by the general class of polycyclic, aromatic hydrocarbons (Allamandola *et al.*, 1987).

The characterization of carbon-bearing phases ranks among the most important goals for an understanding of the evolution of the biogenic elements H, C, N, O, P, and S, and their arrangement into large molecules as the progenitors of life. The analytical capabilities to characterize the carbon-bearing phases and molecular compounds in sample aliquots of nanogram masses are just emerging. For example, Radicati *et al.* (1986) were able to demonstrate that a chondritic particle contained carbon clusters (C_2-C_{15}) and protonated species, as well as CN, CNO, PO_2, PO_3, Cl, OH, and H; they applied Laser Microprobe Mass Spectrometry (LMMS) that can provide *in situ* analyses of some organic molecules on sample areas as small as 1 to 2 μm. Hopefully, such analyses will soon permit comparisons with the investigations from carbonaceous meteorites and other primitive objects of interest to exobiology, as summarized by Wood and Chang (1985) and Allamandola *et al.* (1988).

Embedded in the fine-grained, carbonaceous matrix of some chondritic particles are distinct, polyphase aggregates of extremely small grain size, many with component grains <100 Å in dimension. Typically, such aggregates are rounded, and it was this feature that led to their colloquial reference as "tarballs". They remain poorly characterized in other than bulk composition; the latter is chondritic and thus virtually identical to the bulk composition of the entire host particle. These tarballs provide important evidence that exceedingly small aggregates existed that were composed of elements and minerals(?) which are very similar, if not identical, to the larger hosts; this observation indicates that complex, multi-stage particle accretion processes occurred.

NON-CHONDRITIC PARTICLES are frequently large, single mineral grains or polymineralic aggregates with constituent grain sizes that are large in comparison to those of normal chondritic particles. Minerals composing the general class of non-chondritic particles include olivine, pyroxene, iron sulfides, Ni-Fe compounds (including Ni-Fe carbides), and carbonates. Commonly, finer-grained, chondritic materials adhere to grain surfaces or occur at grain boundaries, suggesting that many of these particles are large clasts broken from a fine-grained matrix.

The subclass of non-chondritic particles includes rare REFRACTORY PARTICLES that were recognized only recently (Zolensky, 1987; McKeegan, 1987), and are composed of high-temperature minerals such as perovskite, fassaite, hibonite, spinel, melilites, Ti-oxides, and glass. They may be related to calcium- and aluminum-rich inclusions in meteorites for which condensation from high temperatures has been established. These refractory particles clearly formed under conditions different from those of chondritic particles.

The extraterrestrial nature of most non-chondritic particles must be established on a particle-by-particle basis. To date, they have generally not received the attention given to chondritic IDPs. It is likely that detailed analysis of many non-chondritic particles will establish an extraterrestrial origin for some; it must be seen whether such particles will form additional, distinct mineralogic or compositional groups that can be accepted as extraterrestrial. For example, many particles from the stratospheric collection consist only of elements with low atomic numbers (*e.g.*, carbon, oxygen, hydrogen, and possibly nitrogen). Their compositional similarity with some particles shed from comet Halley (Jessberger *et al.*, 1988; see Chapter VII) is intriguing, and the widely held belief of a terrestrial origin may be incorrect for some, possibly many. Another example is that many non-chondritic particles consist predominantly of kamacite, magnetite, or iron sulfides. Are they merely the by-products of atmospheric ablation of large meteorites, or are they discrete, interplanetary dust particles? A representative population of particles with well-characterized orbital elements, once obtained by CDCF, will positively resolve these questions.

In summarizing these textural, petrographic, mineralogic, crystallographic, and chemical investigations, the following conclusions are offered: the wide diversity of phase assemblages and crystal habits encountered in cosmic-dust particles is often indicative of distinctly unequilibrated conditions during their formation (Mackinnon and Rietmeijer, 1987). Rods, ribbons, and platelets of enstatite seem to result from direct vapor condensation (Bradley *et al.*, 1983). Some phases, such as Fe-Ni carbide, seem to require reactions of (preexisting) grain surfaces with a carbon-containing gas (Cristofferson and Buseck, 1983). The origin of the silicate melts (glasses) may require partial melting or shock processes, and the hydrated layer-lattice silicates are probably aqueous alteration products of preexisting phases (Zolensky and McSween, 1988). The tarballs suggest multi-stage particle accretion. There is little doubt that the early solar system already afforded a wide range of mineral-forming processes, and that such processes included the reprocessing and alteration of preexisting solids.

Vb) PHYSICAL PROPERTIES

Laboratory measurement of many physical properties on individual specimens, typically <30 μm in diameter, are generally beyond current capabilities. Density and diverse optical properties are significant in calculating parent/daughter orbital divergence (see above), as well as in the interpretation of astronomical observations that currently must assume modeled properties (*e.g.*, albedo, surface roughness, shape factors, mineralogical composition, etc.). A few density measurements have been performed on chondritic particles, yielding values between 0.7 and 2.2 g/cm^3 (Fraundorf *et al.*, 1982).

MID-INFRARED absorption spectra of individual, chondritic particles were accomplished by Sandford and Walker (1985). The particles display a dominant absorption feature (at wavenumbers of approximately 1000 cm^{-1}) that serves to delineate three distinct IR-PARTICLE CLASSES on the basis of their independently verified major minerals (olivine, pyroxene, or layer-lattice silicates). The layer-lattice class displays additional bands indicative of O-H stretching vibrations, O-H-O bending modes, and possibly the presence of hydrocarbons. No IR-spectrum obtained to date from an individual particle matches telescopic observations of specific astrophysical objects. Composite spectra, on the other hand, obtained by mixing of the three major IR-particle classes in specific proportions, can yield reasonable matches to telescopic infrared measurements. For example, spectra of comet Kohoutek require approximately equal proportions of pyroxene and layer-lattice IR-particle types, while those of Halley demand >50% of the olivine-rich particles. The IR-spectra of some layer-lattice silicates duplicate major spectral features of protostellar dust clouds, such as the infrared object W33 (Sandford and Walker, 1985).

Vc) ISOTOPIC MEASUREMENTS

A number of isotopic measurements have been performed on IDPs. Some elements yield isotope relationships consistent with solar-system values, others display significant anomalies (*e.g.*, McKeegan *et al.*, 1985).

Isotopic analyses of Mg, Si, and Ca yield values that are essentially normal, yet sample quantities are small, and minerals are so minute that isotopic analyses must generally be performed without the benefits of mineral separates, acid leaches, etc., the traditional precursor steps in most mass-spectrometric isotope analyses of natural samples. Fortunately, the advent of Secondary Ion Mass Spectrometry (SIMS) in the form of ion microprobes allows direct *in situ* characterization of some isotopes on dimensional scales appropriate for IDPs.

Substantial hydrogen isotopic anomalies have been observed by ion probe. The D/H (deuterium/hydrogen) values of chondritic particles frequently display substantial deuterium enrichments and depletions relative to standard, terrestrial ocean water (Zinner *et al.*, 1983). The most recent work demonstrates that these anomalies are spatially associated with carbon phases, and that the deuterium enrichments/depletions are highly localized (McKeegan *et al.*, 1987). The highest concentrations reported to date are δD >9000 ‰, the most deuterium-rich natural material ever observed, and highly suggestive of an inclusion of interstellar matter within the carbonaceous matrix (McKeegan *et al.*, 1987; Zinner, 1988).

Evidence is also emerging for small, yet significant, variations in carbon isotopes of chondritic particles; the largest variations in δ^{13}C between individual particles measured to date are 40 ‰ (McKeegan *et al.*, 1985). This anomalous carbon, however, is much more homogeneously distributed through individual particles and is not spatially associated with the carrier phases of the D-anomalies.

Some of the refractory particles have been analyzed for oxygen isotopes. They displayed substantial ^{16}O enrichments, rendering their extraterrestrial origin beyond doubt (McKeegan, 1987).

Vd) COMPARISON WITH PRIMITIVE METEORITES

Chondritic IDPs have many similarities with the most primitive meteorites, the carbonaceous chondrites. Although these meteorites may also be classified into a number of distinct subclasses on the basis of constituent minerals and specific chemical properties, they all share the common property of having bulk compositions that are remarkably similar to that of the solar photosphere (with the exception of a few volatile elements); all solids composing the inner planets are fractionated by comparison. This remarkable correspondence in bulk composition, together with the established formation ages of most meteorites at about 4.6 billion years, provides the basic link to view them as probes of early solar-system processes and to consider them the most "primitive" solids in the solar system. Identical arguments apply to "chondritic" IDPs recovered on Earth, save absolute chronology, which is currently beyond analytical capabilities. The primitive nature of chondritic IDPs and their utility in understanding early solar-system processes is widely accepted. Many expert articles, the result of a recent conference on "Meteorites in the Early Solar System", are contained in Kerridge and Matthews (1988).

It must be noted, however, that the analogies of chondritic IDPs and carbonaceous chondrites pertain only to the fine-grained matrices of the much more massive meteorites, because chondrules and other macroscopic inclusions (typically millimeters in size) that are common in these meteorites are not generally present in the dust collections. The underrepresentation of large meteorite components may simply be a matter of dimensional scale and selection during atmospheric entry.

Most of the minerals identified in chondritic dust particles occur in primitive meteorites as well, yet specific details of crystal chemistry, crystallographic properties, mineral habits, overall modal mineralogy and paragenesis, and sample texture on scales <1 μm differ substantially to the degree that different conditions of formation and/or subsequent evolution are required. In particular, the measured densities and observed porosities of chondritic particles are either considerably lower or higher than those of any primitive meteorite; the delicate microstructures characterizing many IDPs are absent in meteorites. The mineral grain size of refractory particles is typically one to two orders of magnitude smaller than that observed in refractory inclusions in chondrites. The hydrous chondritic particles bear the closest resemblance to CI and CM meteorite matrices, yet important differences exist in the modal frequency of major layer-lattice silicates (Tameoka and Buseck, 1986; Brownlee *et al.*, 1987; Bradley *et al.*, 1988; Zolensky and McSween, 1988). In addition, some deuterium enrichments observed in interplanetary particles exceed those reported for meteorites (Zinner, 1988). Carbon concentrations of chondritic dust particles are generally higher than for any chondrite, and are closer to solar abundance than those of chondrites (Blanford *et al.*, 1988). Some components in IDPs seem unique, such as the tarballs and the pyroxene whiskers and platelets.

These differences must be viewed as significant. They constitute cumulative evidence to consider some chondritic particles analyzed to date as the most pristine extraterrestrial materials yet studied. As a minimum, the detailed laboratory characterization of IDPs has proven to be highly complementary to ongoing investigations of primitive meteorites.

Ve) ANALYTICAL INSTRUMENTATION

As indicated repeatedly, the nature and quality of these analytical results was made possible only by employing modern, state-of-the-art, analytical instrumentation. Some of the methods currently in use were adopted from other developments, yet some were specifically designed and developed by dust researchers. The small sample masses involved, and the minute scales of observation dictate that cosmic-dust researchers participate in the advancement of microanalytical instrumentation and methods. Cosmic-dust investigators have contributed substantially to the challenge of extracting scientific information from ever decreasing sample volumes of natural materials. Continued contributions toward improved microanalytical capabilities by these individuals and their specialized staffs can be expected in the future as well. Such contributions will range from rendering current, sophisticated, and time-consuming measurements into more efficient and widely used routines, to the introduction of innovative measurements beyond current capabilities. These efforts will also include methods for sample handling, a non-trivial issue for microscopically small specimens, and methods of sample preparation for specific measurements. For example, many of the results obtained to date exist only because the capability was established to microtome micron-sized particles into several thin sections of some 1000 Å thickness (Bradley and Brownlee, 1986).

Continued support of cosmic-dust analyses and advancement of state-of-the-art analytical methods is an important ingredient for the success of CDCF. These efforts must be viewed as part of the overall system capability in the Mission Analysis Phase of the project. These preparatory efforts will control, in large measure, the quality and quantity of scientific information that can be extracted from the particles captured by CDCF and subsequently returned to Earth. An excellent summary of current analytical capabilities, as well as those desired and reasonably achievable in the near future, is presented by the Planetary Materials and Geochemistry Group (Burnett, 1988).

A SUMMARIZING EPILOGUE of the current state of affairs in the analysis of extraterrestrial dust particles is as follows: sophisticated analyses of minute specimens performed to date have yielded significant results not previously known from other primitive solar-system materials. Similar contributions, including new measurements, can be expected in the future; however, all efforts will continue to suffer from a single, major shortcoming: the inability to place these observations unambiguously into their proper astrophysical context. The particles remain parentless. Trajectory measurements are possible in LEO and analyzable particle residues can be returned to Earth. The Cosmic Dust Collection Facility on *Freedom* will afford the analysis of materials from known sources. This constitutes the major objective of CDCF, one that is technically feasible and that otherwise can only be accomplished by dedicated missions to a limited number of primitive solar-system bodies.

VI) INSTRUMENT DEVELOPMENT: PROOF OF CONCEPT

This is a general introduction of the concepts behind and to the demonstrated capabilities of instrumentation currently contemplated for CDCF. Major development tasks are described that are common to both agency- and PI-provided instruments as discussed at a number of workshops. It is recognized that specific designs and solutions to these general problems will be the subject of individual flight proposals, including specific idiosyncrasies and development tasks that are beyond the scope of this report.

VIa) TRAJECTORY SENSORS

All trajectory-sensor concepts currently under consideration either have some degree of flight heritage and/or were tested in a variety of hypervelocity impact facilities. Conceptually, they acquire signals in the form of:

a) Acoustic energy or shock waves emanating from an impact point.

b) Electrical charges in the form of ions or electrons that are produced by thermal ionization upon hypervelocity impact.

c) Change in net polarization of thin films caused by displacement/disordering of dipoles during cratering/penetration events.

d) Induced charge(s) in a carefully biased electrostatic grid system as it is traversed by naturally charged particles.

Most principles have long been used in cosmic-dust flight instruments and were successfully employed as recently as the GIOTTO and VEGA missions to comet Halley in 1986; some are considered flight candidates for the CRAF mission. An empirical database exists that demonstrates the successful acquisition of useful signals based on the principles listed above; the list may not be considered exclusive, however, as innovative detection principles may emerge to diagnose small hypervelocity particles in free flight.

The CDCF objectives mandate accurate trajectory determinations. A $<1\%$ error in velocity measurement is the current design goal, although more adequate requirements -- either relaxed or tightened -- can be given only after additional parent/daughter orbital-divergence calculations are accomplished (see Chapter IV). The accuracy in the measurement of angular resolution will be better defined by such calculations as well; the current design goal is specified at $\pm 1°$. While these design goals provide technical challenges, they do not require innovative technology.

Suitably accurate velocities can only be obtained by direct measurement of the transit time between two or more sensors with well-known separations. Most previous flight instruments employing the detection principles listed above utilized only a single sensor that diagnosed the exact arrival time of a projectile and determined either its momentum or kinetic energy. Utilization of multiple sensor stations necessitates substantial mechanical and electronic reconfiguration of past flight sensors for the precise measurement of particle transit times and resultant velocities. Sequential detection of individual particles by several sensors constitutes a major development task for CDCF instrumentation.

The determination of a particle's state vector also demands knowledge of the precise locations of the penetration points through at least two sensor planes, or that other means be devised to determine the particle's flight path relative to an instrument reference frame. This is a new challenge for some sensors flown previously, yet it is accommodated by others with relative ease. Specific instrument coordinates relative to Space Station Freedom's center of gravity will have to be tracked continuously for the reconstruction of geocentric orbits. This is accomplished by the specific mechanical and electronic architecture of the facility itself, and includes acquisition of facility/instrument pointing knowledge, possibly via dedicated star tracker, and access to the spacecraft's navigational data system, either in real time or via precisely synchronized clocks.

Almost without exception, sensors exposed in previous flight experiments were of low mechanical transparency; many monitored genuine cratering events on relatively thick witness plates. The particle-capture objective of CDCF demands highly transparent sensor systems that minimize physical interference with the traversing particle, so as not to unduly compromise the integrity of a specimen before it reaches the capture medium. Excessive interference with the particle would also raise the concern that it could be intolerably decelerated or that other modifications/ imprecisions in trajectory determination might be introduced. Empirical insight in the form of small-scale hypervelocity impact experiments are needed to address some of these issues.

On the basis of the details given above, most previously employed sensors need considerable modification to be included into CDCF. They must accommodate a precise measurement of transit time between sensors, provide information on particle location, and be of a highly transparent nature in a mechanical sense. Conceptual solutions for these modifications were offered during workshops and other formal and informal communications; specific approaches will be the subject of individual flight-instrument proposals.

It is paramount that suitable breadboard models be manufactured soon, and that they be tested extensively in terrestrial impact facilities. Compared to the dynamic range of natural particles, these laboratory impact simulations can only be of limited scope. It is highly desirable to subject different CDCF sensors to actual flight tests in LEO as targets of opportunity arise in the 1990 to 1992 time frame.

VIb) CAPTURE DEVICES FOR HYPERVELOCITY PARTICLES

In general, the kinetic energy of natural impactors vastly exceeds the specific heats of fusion and vaporization of common silicates; therefore, the purposefully designed capture device must aim at maximizing the dissipation of this energy into the capture medium. Deceleration by molecular collisions (gaseous medium) or viscous drag (liquids, etc.) seems impractical in LEO. The practical method of choice is deceleration by impact processes. Fundamentally, this method "works" as illustrated by the successful analysis of projectile residues on diverse hardware exposed and returned from LEO, such as Solar Maximum satellite thermal blankets and thermal control louvres (see below). However, the dedicated capture devices on CDCF must be purposefully optimized and engineered.

Totally nondestructive deceleration and the recovery of pristine, unmodified cosmic-dust specimens does not seem possible in most cases with collisional capture techniques, considering the distribution of encounter velocities (see Figure 1). The technical challenge is to devise means for the least destructive deceleration. The application of shock physics allows identification of suitable approaches that will lead to carefully engineered, optimized capture devices. Yet other considerations will be of concern as well, such as specific cosmochemical objectives that control selection and chemical purity of the materials from which the collectors may be fabricated. Specific collector designs may be optimized for "large" and "small" impactors, for high-velocity (interstellar) particles, or to concentrate almost exclusively on low-velocity impactors that are offered to an anti-apex pointing collector. Lastly, procedures must be developed in order to recover trapped particle residues from the capture medium while preserving their suitability for subsequent analysis. This serves to illustrate that a wide variety of considerations will affect specific designs. It is most likely that various types of collector devices will be exposed on CDCF that accommodate, in complementary fashion, the unusually wide range of dynamic properties of natural dust particles and the wide variety of important, cosmochemical investigations.

Four basic approaches to collect hypervelocity particles are presently under consideration and conceptual study: (1) the use of specialized, low-density, high-porosity foams; (2) the use of multiply stacked, thin films; (3) the use of traditional (infinite half-space) witness plates; and (4) capture cells.

Materials of extremely low bulk density (<0.05 g/cm^3) are currently available in the form of highly porous foams. The shock stress generated upon impact depends strongly on the bulk density and acoustic impedance of both the target and impactor. By keeping the target density as low as possible, the shock stress and associated temperatures within the projectile may be engineered -- within reason -- to be correspondingly low. On the basis of modest extrapolation of existing equation-of-state data for low-density foams (Marsh, 1980), it appears to be possible to keep the shock stress below the solid/liquid phase transition for most dense silicates (approximately 40 to 60 GPa) colliding with such low-density foams at typical cosmic velocities (approximately 15 km/s). However, the low-density/low shock-stress arguments apply only to foams that are of proper dimensional scales; the thickness of walls, septa, etc. (*i.e.*, of all solids making up the foam) must be substantially smaller than typical impactor dimensions. These scaling considerations identify aerogel, a commercially available silica foam, as being suitable because it is made of irregular chains and clusters of SiO_4 tetrahedra some 30 to 50 Å across (Fricke, 1988). Aerogel has been employed successfully in laboratory capture experiments where non-porous silicate impactors remained unmelted at light-gas gun velocities up to 6 km/s (Tsou *et al.*, 1987).

The multiply stacked, thin-film capture method relates to the generation (and purposeful engineering) of shock pulses with extremely short durations, which in turn precipitate very rapid stress attenuation in the impactor. This may keep substantial volumes of the projectiles, located towards the rear, from experiencing high shock stresses and temperatures. The thinner the foils, the shorter the pulse duration, resulting in lower average shock stresses throughout the projectiles. In practice, the thinnest foils available are on the order of 300 to 500 Å in thickness. Suitably scaled laboratory experiments are necessary to quantify specific collisional outcomes and to extrapolate the mass of unmelted particle fragments that may be captured at cosmic velocities.

A third collection approach relates to the deployment of carefully prepared, "thick" target plates that will, by design, result in *bona fide* hypervelocity cratering events. Melted and vaporized projectile species may be found inside these craters and their immediate surroundings. Such devices are clearly the choice for extremely small impactors in which the above described dimensional scaling relationships are violated by currently practical thicknesses of foam walls or thin films.

Capture cells are thick-walled, box-like structures with the side exposed to space covered by a thin film. Objects penetrate this thin-film membrane and impact into the side and/or rear surface(s) of the capture cell. The film is thin enough to permit penetration of small particles, yet durable enough to retain the ejecta after the particle impacts the cell interior. By keeping all capture-cell dimensions small, the projectile residues can be concentrated over a modest surface area.

While application of shock principles is a necessary first step in the design of capture devices, it remains unclear as to whether sufficient energy is indeed partitioned into the target medium. Intolerable projectile heating by frictional processes may occur in low-density foams or during repeated shocks generated while penetrating a series of thin foils. Furthermore, collisional fragmentation of many particles may not be avoided in view of the fact that dynamic tensile strengths of dense silicates are as low as 0.1 to 0.2 GPa, stresses that are readily exceeded under most foreseeable conditions.

Some of these questions and uncertainties can be addressed experimentally by making use of light-gas guns, plasma-drag instruments, and electrostatic accelerators. Unfortunately, many of the known natural conditions may not be simulated realistically because each launch method is limited to specific velocities and an associated restricted range of projectile mass. Furthermore, highly fluffy particles of low cohesive strength do not survive current laboratory acceleration rates. Theoretical studies are needed to extrapolate the limited laboratory findings to the expected range of natural impact conditions. It is also extremely desirable to expose prototype collectors in space and to expand on and/or verify the laboratory results and associated extrapolations. Simple, entirely passive experiments in LEO should suffice to test new capture concepts.

VIc) ANALYSIS OF SPACE EXPOSED SURFACES

We now turn to a few surfaces that were exposed in space, returned to Earth, and analyzed for impact features and associated projectile residues; such surfaces presented unplanned opportunities to study the effects of space exposure. The purpose is to demonstrate that substantial scientific information could be extracted from such surfaces, although they were never intended to collect cosmic dust.

Studies of this kind started with the analysis of impact craters on the windows of the Apollo and Skylab spacecraft, included parts of Surveyor III returned from the Moon, and progressed to a variety of witness plates exposed on the Shuttle, including evaluation of impact damage to some Shuttle windows and thermal tiles. Thermal blankets (*i.e.*, multiply stacked foils) and aluminum louvres (modestly thin witness plates) were recovered from the Solar Maximum satellite after some four years of space exposure; their cumulative time-area product exceeds those of all previous experiments combined, prompting extensive laboratory analyses of their impact features. These Solar Max materials contained approximately 2000 impact features, either craters or penetration holes (Warren *et al.*, 1988). Projectile residues were observed and analyzed in a number of instances. Their chemical characterization lead to the recognition of compositionally diverse natural impactors and of a wide variety of orbital-debris particles, the latter including a variety of flaked paints, aluminum oxide from solid-fuel rocket firings, frozen urine, and other impactors (Schramm *et al.*, 1986; Warren *et al.*, 1988). Of great significance to the collection of natural particles in LEO is the recovery of unmelted olivine fragments (Rietmeijer and Blanford, 1988) and of hydrated silicates (Bradley *et al.*, 1986).

These findings on inferior collector devices provide proof that:

1) The occasional recovery of unmelted particle fragments in LEO is possible *via* collisional deceleration.

2) Substantial information may be extracted from melted and vaporized particle remnants; the bulk composition of individual particles can be obtained, meaningful compositional groupings can be established, and man-made contaminants are readily distinguished, in most cases, from natural dust particles.

These results attest to the power of modern, sophisticated analytical methods in the analysis of small sample masses, including exceedingly thin melt layers and vapor deposits.

The information obtained from the Solar Maximum satellite will hopefully be augmented and substantially surpassed by the retrieval (November, 1989) of the Long Duration Exposure Facility (LDEF), an approximately 100 m^2 free-flyer that has been exposed to space for some five years. Approximately 8 m^2 were dedicated to the capture of cosmic-dust particles. Comparisons among a variety of capture approaches should be possible, as individual PI-instruments employed (a) capture cells, (b) multiply stacked-foil configurations, and (c) diverse witness plates. A few hundred craters >500 μm are expected on LDEF, a totally passive platform that did not permit active trajectory sensors.

In summary, there exists substantial empirical proof from space-exposed surfaces, none of them designed to capture hypervelocity particles, that the collection and retrieval of cosmic dust is a realistic goal for CDCF, and that significant scientific information can be extracted from the recovered residues. Purposefully conceived, substantially improved collectors will be exposed on CDCF. Specific CDCF development efforts will aim at minimizing particle degradation, permitting the recovery of unmelted particle fragments; specific designs may be tailored to special cosmochemical objectives by prudent selection and control of collector materials. Improved recovery of particle residues, once trapped, constitutes another development task. All efforts must be viewed as optimization of existing concepts and methods; some necessitate incorporation of specialized, state-of-the-art materials, such as the exceedingly low-density/high-porosity foams, or high-purity, thin films, yet none depend on innovative technologies.

VII) RELATION OF CDCF TO OTHER PROGRAMS

Cosmic-dust particles are of principal interest to investigators that undertake a wide variety of scientific efforts concerned with the early solar system. Characterization of dust particles is an important ingredient of multi-disciplinary studies related to the condensation of the solar nebula and the formation of planets, to the evolution of biogenic elements and compounds, and to a variety of astrophysical and cosmochemical investigations related to the formation of stars.

VIIa) PLANETARY SCIENCE PROGRAMS AND DEDICATED MISSIONS

Interplanetary dust particles are recognized as a special class of extraterrestrial material that is, in part, linked to comets. The high-volatile content of comets, as well as their orbits at the fringes of the solar system suggest conditions during solar-nebula condensation that differed substantially from those yielding the terrestrial planets. Even if this view were correct only for the icy components of comets to the exclusion of solid silicates, there is little doubt that the latter were preserved exceptionally well in these cold, cometary matrices throughout solar-system history. They certainly escaped much of the thermal processing typical of the inner planets and have the potential to be among the least modified and recycled matter in the solar system. They may reflect conditions and processes in the condensing nebula better than any other class of extraterrestrial material.

In addition, the possibility exists that pre-existing, interstellar grains -- a likely component present during nebula condensation -- were incorporated into the earliest solids; cometary particles are a most logical place to search for such materials. If identified, the unique opportunity would arise to characterize materials predating the solar system in unprecedented detail. Furthermore, CDCF will be capable of trapping particles from present interstellar sources, provided such objects reach the inner solar system in sufficient numbers.

Recognition of this significant scientific potential forms the basis for diverse science programs that sponsor the acquisition of cosmic dust in the stratosphere, in deep-sea sediments, and in pre-industrial, polar ices, and that support their detailed physical, mineralogical, chemical, isotopic, and organic characterization. Such activities are carried out by a number of national and international agencies and organizations. Unquestionably, NASA's Extraterrestrial Materials Program provided the impetus and leadership, yet foreign agencies in England, West Germany, Holland, France, Japan, the Soviet Union, and the People's Republic of China are mounting concerted efforts of their own to acquire and study such particles, including their collection in LEO.

After exploratory investigation of the inner planets and some surveying of the outer planets, comets naturally became high-priority targets for dedicated missions. Past flight programs, Earth-based remote sensing observations, and the analyses of extraterrestrial materials have led to the study of "primitive" comets as a highly attractive, scientifically rewarding "next step" in the current exploration strategies of the solar system (NASA, 1982, 1986; ESA 1984).

The laboratory characterization of cosmic-dust particles relates prominently and directly to the planning of such dedicated missions to comets and other primitive bodies, whether fly-by, rendezvous, landing, and/or sample return. This is amply demonstrated by the mass-spectrometric analysis of particles emanating from comet Halley by the highly successful PIA and PUMA instruments on the GIOTTO and VEGA spacecraft (Kissel *et al.*, 1986a, 1986b). Interpretation of the spectra obtained from Halley has substantially benefited from extraterrestrial particles that were collected and analyzed on Earth.

VIIb) GIOTTO/VEGA MISSIONS TO COMET HALLEY

Most particles released by Halley are of sub-micron size (typically $<10^{-13}$ g in mass). They reveal wide compositional variety and thereby mineralogical diversity; Jessberger *et al.* (1988) provide an excellent summary. Some four major particle classes are distinguished that vary diagnostically in the major elements C, O, Mg, Fe, and Si; furthermore, the classes correlate with additional elements such that the presence of silicates and non-silicates (low Z-number particles) can be established with confidence. The study of the grain-size distributions and compositional heterogeneities on scales <1 μm in dust particles (Bradley, 1988) and carbonaceous chondrite matrices (Brownlee *et al.*, 1987) thus becomes significant. Some Halley spectra appear to be compatible with, or seemingly dominated by, specific phases known from dust studies, such as hydrated layer-lattice silicates or FeS grains; other particles seem to be dominated by olivine or pyroxene. The frequency distribution of individual Fe/(Fe+Mg) measurements on Halley is not duplicated in any known extraterrestrial material; it most closely resembles that expected from anhydrous, chondritic dust particles. The latter, however, are demonstrably not the only silicates composing all Halley's particles. Non-silicates released from Halley are both intriguing and abundant; they were dubbed "CHON" particles because they are composed almost entirely of C, H, O, and N, albeit in highly variable proportions (*e.g.*, hydrogen may vary from some 3 to 94%, carbon from 3 to 65%); distinct compositional clusters have been recognized among the CHON particles. They have no known analogues in extraterrestrial samples. However, the detailed characterization of carbonaceous material in cosmic dust and primitive meteorites on scales <1 μm is not currently possible, although encouraging advancements of analytical methods are in progress.

VIIc) COMET RENDEZVOUS/ ASTEROID FLY-BY MISSION (CRAF)

The CRAF spacecraft will fly by an asteroid enroute to a comet; it will then rendezvous with the comet, perform extended orbital observations, and culminate with the deployment of an instrument package on the comet's surface for *in situ* measurements, including chemical and mineralogical analyses. Current dust investigations in the laboratory may sharpen the focus of the contemplated CRAF instruments and will alert the mission planners to crucial measurements. Having characterized many particle properties and their variability in the laboratory, the performance requirements for analytical instruments can be detailed, some especially rewarding measurements can be identified, and some suitable analogue materials for the testing and calibration of analytical flight instruments can be specified and manufactured in quantity.

VIId) COMET SAMPLE RETURN MISSION (ROSETTA)

The return of comet samples to Earth has been studied extensively and a number of mission scenarios exist. ROSETTA is the mission currently contemplated and jointly studied by NASA and ESA. An associated report (*ROSETTA*, 1988) contains an authoritative evaluation of the scientific merits of studying comets in general, and that of returned samples specifically. The report concludes, as implied by the mission's formal name, that "Cometary samples are not just samples of one of the many minor bodies in the solar system, but they carry the primordial material out of which all planetary objects were formed approximately 4.6 billion years ago. The Rosetta Mission is a planetary mission which leads to the roots of the planetary system."

Much of the scientific rational for ROSETTA also applies to CDCF on the *Freedom* Station; CDCF may be viewed as an important precursor of ROSETTA. Current and future knowledge gained from the laboratory analysis of extraterrestrial particles will be an important guide in addressing sample collection and preservation during this mission, and will form the major basis for placing the results of this dedicated mission to a single comet into a more general astrophysical framework. In addition, many of the analytical capabilities developed by cosmic-dust researchers, including sample handling, preparation, and curation methods, will be a crucial part in the planning and execution of a successful ROSETTA sample-analysis program. Many analytical methods and skills for the ROSETTA mission will emerge from the pool of dust researchers and their laboratories.

While a variety of other cometary-mission scenarios exist, including the atomized sample return by the Japanese Space Agency, the CRAF and ROSETTA missions are considered the major, representative candidates. Any other cometary mission scenario will benefit from the collection and detailed analysis of cosmic-dust samples: specific mission objectives will be sharpened, associated instrument performance can be defined and fine-tuned, and data obtained remotely can be related to actual samples that will have been studied by a large number of laboratory methods.

The largest potential for CDCF within the contexts of cometary science and dedicated missions rests in the fact that any interplanetary particle population should contain samples from a number of comets. Orbit-evolution times and particle lifetimes are calculated to be as long as 10^5 to 10^6 years (*e.g.*, Grün *et al.*, 1985; Jackson, 1987; Gustafson *et al.*, 1987). This leads to the expectation that any particle collection will contain materials from many short- and long-period comets. CDCF is conceived and purposefully designed to associate specific particles with either individual comets, selected subgroups of comets, or comets as a class. The cometary solids retrieved by CDCF may thus serve for proxy analyses of a (poorly defined) number of comets. This capability appears to be unique to CDCF and constitutes one of its strongest justifications.

In summary, the particles retrieved from CDCF, together with those collected on Earth, will form a broad context within which the results of dedicated cometary missions will be better interpreted. Even if these particles were not direct duplicates of those encountered during specific missions, they would represent the most suitable natural equivalents and analogues.

VIIe) LIFE-SCIENCES PROGRAMS

Most early solar-system processes of interest to planetary sciences are of similar interest to life sciences, and specifically to exobiology. The principal goal of exobiology is to understand the origin, evolution, and distribution of life. To meet this goal, the initial distribution of biogenic elements and their incorporation into compounds must be placed in the context of the physical and chemical evolution of the solar system. The acquisition and detailed analysis of primitive solar-system materials therefore becomes an integral and important part of research into the origin of life on Earth and the potential for life elsewhere.

The interest of exobiology in the analysis of primitive meteorites is long-standing, and exobiology studies of cosmic-dust particles recovered from the stratosphere are commencing. There is active participation in the analysis of Halley data and flight instruments for CRAF are being readied. Exobiologists have contributed substantially to the planning and execution of ROSETTA. Other space instrumentation is being considered and important remote sensing observations are being conducted. Many study reports issued this decade attest to the importance and to the variety of opportunities offered to exobiology by investigations in space and by the laboratory analysis of extraterrestrial materials (Wood and Chang, 1985; Milne *et al.*, 1985; Hartmann *et al.*, 1985; Nuth and Spencer, 1988; Klein, 1989).

Of interest are the initial abundance distributions of biogenic elements (C, H, N, O, P, and S), the physical and chemical pathways they had taken during nebula condensation and planet formation, the identification of specific compounds that actually formed and are present in primitive solar-system objects, the reactions and processes responsible for the formation of these compounds, and an evaluation of which compounds may be considered significant in the evolution of life. Improved understanding of these processes will then provide important boundary conditions for laboratory investigations into the synthesis of important precursor forms of life.

VIIf) ASTROPHYSICS PROGRAMS

The relation of CDCF as part of ongoing efforts within the context of planetary exploration and exobiology programs is well established and formalized *via* a Memorandum of Agreement. Currently, no formal connections or collaborations with the Astrophysics Division (Code EZ) exist at present, although there are informal ties between individual researchers.

The laboratory study of fine-grained interplanetary matter is in its infancy, although the capability for making highly sophisticated measurements and contributions now exists. Beyond question, some of these contributions are of significance to research in astrophysics (*e.g.*, Nuth and Stencel, 1985). Most dust researchers have acquired some prerequisite skills in the understanding of nebula condensation, star formation, and nucleosynthesis in order to relate the dust observations to astrophysical research (*e.g.*, Kerridge and Matthews, 1988). Participation by astrophysicists in the current dust-analysis program and, in particular, during the mature CDCF analysis phase is highly desirable. Such efforts will focus on the opportunity to characterize the smallest, primitive matter in our own solar system, and therefore may provide analogues of interstellar phenomena and processes (Nuth, 1988). The prospect of identifying pre-solar, as well as contemporary interstellar grains in the particle residues returned from CDCF promises to provide information about star and planetary formation, as well as nucleosynthesis.

VIIg) CHARACTERIZATION OF ORBITAL DEBRIS

CDCF will continuously monitor the population of fine-grained, man-made orbital debris, as well as that of natural particles. All particles combine to define the collisional hazard in near Earth space, a subject that has significant ramifications on spacecraft safety and associated designs. Efforts in formulating internationally accepted mitigation policies of man-made debris are currently in progress.

The CDCF instruments will measure the trajectories of all particles it encounters in LEO, trapping them in the collectors for return to and detailed analysis on Earth. As exemplified by the analysis of surfaces collected during repair of the Solar Maximum satellite, a substantial chemical variety of man-made particles could be demonstrated and must be traced to multiple sources. It is inevitable that CDCF will contribute to the characterization of man-made debris, because the study of natural particles requires the identification of man-made contaminants. *In situ* characterization of the dynamic properties of orbital debris and identification of the most prolific sources of debris constitutes the first step in evaluating the collisional hazard to future spacecraft in LEO, and to formulating national and international policy for its mitigation. CDCF will make substantial contributions to these basic characterizations and is designed to monitor short- and long-term temporal variations of specific particle sources.

No formal relations between the CDCF Project and programs or organizations responsible for orbital-debris characterizations (OAST) currently exist, yet informal contacts are maintained by some CDCF participants who are also involved in the forefront of orbital-debris studies.

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16. Abstract

This report summarizes the science objectives for the Cosmic Dust Collection Facility (CDCF) on Space Station Freedom and relates these objectives to ongoing science programs and mission planning within NASA. The purpose of this report is to illustrate the potential of the CDCF project within the broad context of early solar-system sciences that emphasize the study of primitive objects in state-of-the-art analytical and experimental laboratories on Earth.
The report focuses on current knowledge about the sources of cosmic dust and their associated orbital dynamics, and it reviews the results of modern microanalytical investigations of extraterrestrial dust particles collected on Earth. Major areas of scientific inquiry and uncertainty are identified and it is shown how CDCF will contribute to their solution. General facility and instrument concepts that need to be pursued are introduced, and the major development tasks that are needed to attain the scientific objectives of the CDCF project are identified.

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